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**CONTAMINANT TRANSPORT AND ATTENUATION IN THE
NORTHERN ENVIRONMENT - CHALLENGES AND
OPPORTUNITIES FOR MINE RECLAMATION**

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Contaminant Transport and Attenuation in the Northern Environment – Challenges and Opportunities for Mine Reclamation

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Abstract

While chemical reactions leading to the transport and attenuation of contaminants in the natural environment are fundamentally the same under all climatic conditions, the northern setting often introduces complications that are not simply related to rate differences due to temperature. Successful mine reclamation in northern regions depends on accurate predictions of the chemical behavior of contaminants released or generated by mining activities. Based on case studies of natural acid rock drainage and mobility of potentially deleterious species in exploration and closed mine sites in the Yukon Territory, common processes leading to the transport and attenuation of contaminants in cold climates are reviewed. While cryogenic precipitation, coprecipitation and sorption are significant metal attenuation mechanisms in small streams, dilution is the major mechanism in larger water courses. Reducing conditions generated under an ice cover, however, may lead to the remobilization of precipitated oxides and the associated adsorbed metals. Flushing of efflorescent salts deposited on exposed surfaces during dry seasons may also render dilution insufficient to ensure acceptable water quality during spring freshet or heavy fall rains. Although there is ample evidence of contaminant removal through wetland processes and sorption reactions in unfrozen soil, the natural capacity of local wetland and soil systems to attenuate contaminant transport and their performance at low temperatures require more research. The challenge of mine reclamation in high latitudes lies in integrating chemical stability data with information on site-specific conditions to take advantage of what nature has to offer in order to arrive at a scheme with as negligible environmental risks and impacts as possible.

Introduction

One of the primary objectives of mining reclamation is to return the affected land to its previous level of productivity in a form compatible with the local landscape. Implicit in this objective is the requirement that all mine waste generated is properly disposed of to assure long-term chemical and physical stability. While chemical reactions leading to the transport and attenuation of contaminants in the natural environment are fundamentally the same under all climatic conditions, the northern setting often introduces complications that are not simply related to rate differences due to temperature. Successful mining reclamation in northern regions depends on accurate predictions of the chemical behavior of contaminants released or generated by mining activities. Case studies of natural acid rock drainage and mobility of potentially deleterious species in exploration and closed mine sites in the Yukon Territory provide a good base for reviewing the significance of common processes leading to the transport and attenuation of contaminants in cold climates.

Study sites relevant to this review include the Eagle Plain and Engineering Creek areas along the Dempster Highway, the Keno Hill mining district northeast of Mayo, the

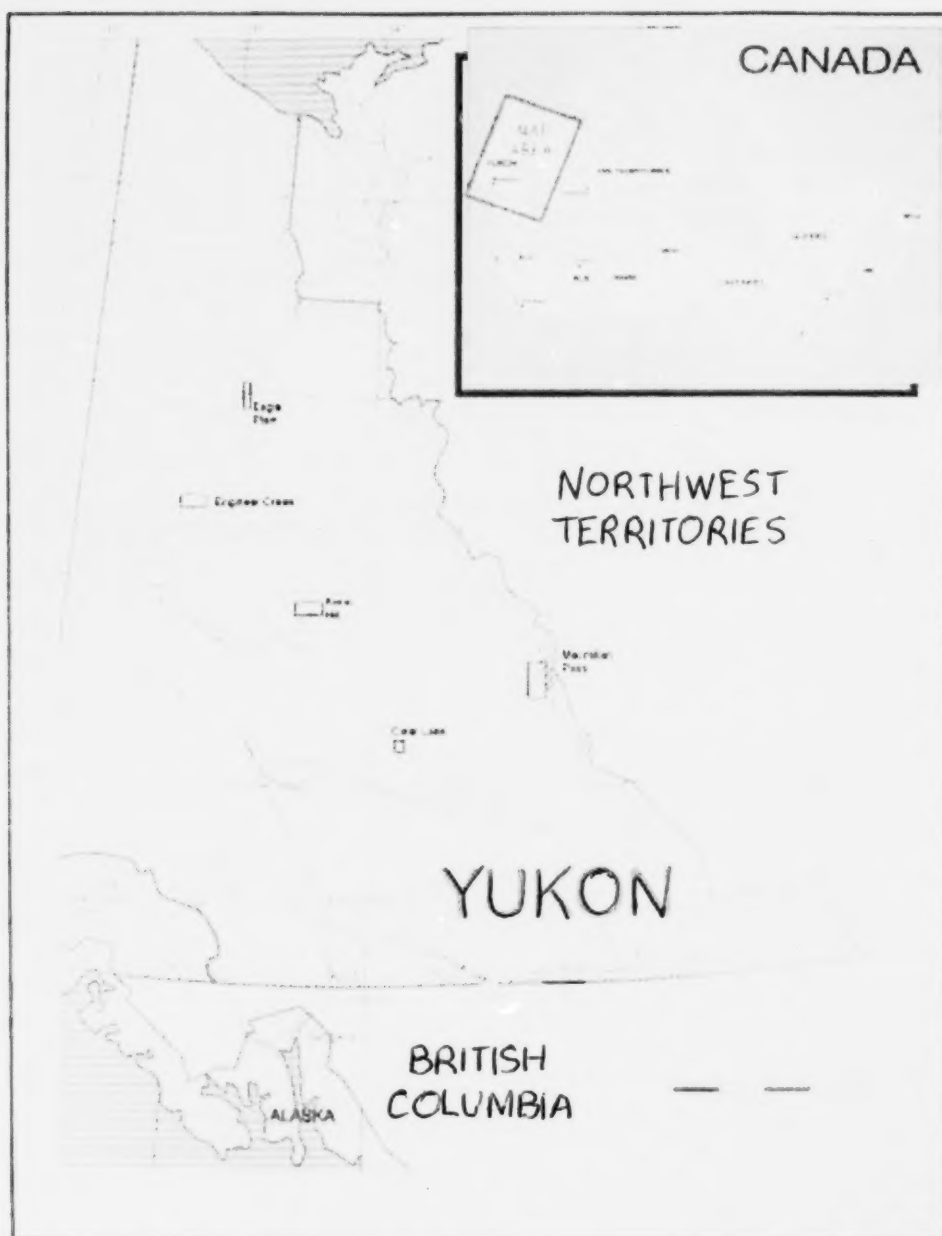


Figure 1. Location map of the study areas.

Clear Lake deposit northwest of Ross River and the Macmillan Pass area near the Yukon-Northwest Territory border (Figure 1). The general settings of these sites are described in Kwong and Whitley (1993), Kwong et al. (1997) and Kwong and Lawrence (1998). Detailed contaminant transport and attenuation mechanisms occurring in each of these study areas are discussed in the above papers. It is the purpose of this communication to provide an overview of the general observations made and ponder their implications for mine reclamation and decommissioning in northern regions.

Contaminant Mobilization and Transport Processes in Cold Regions

For the purpose of this review, only processes leading to the remobilization of contaminants from a point source (in this case, a mineralized area) are considered. Since atmospheric transport is not an issue in any of the sites studied, the primary focus rests with contaminant transport in the aqueous phase.

Table 1 shows examples of contaminated drainage observed in the study areas. Most of the occurrences were in the form of seeps or ponded water. It is clear from the data shown that acidic drainage is commonly associated with a high contaminant load. However, near-neutral drainage is not necessarily devoid of contamination. For example, ponded water found in the Rio Plata occurrence in the Keno Hill mining district had a pH value of 7.3 but a dissolved zinc concentration as high as 109 mg/L (Table 1). Depending on chemical reactions occurring along the drainage flowpaths, dissolved contaminants may be transported varied distances from the source areas.

Table 1. Examples of contaminated drainage in selected Yukon study sites

	Macmillan Pass	Clear lake	Dempster	Keno Hill
pH	2.98	1.85	3.00	7.30
SO ₄ mg/L	2290	8220	21000	1886
Al mg/L	156	324	1290	<0.005
As mg/L	0.033	1.04	7.81	<0.04
Pb mg/L	<0.02	0.54	2.12	0.013
Zn mg/L	6.07	71.8	154	109

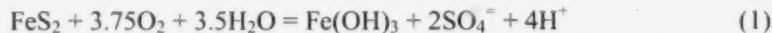
In exposed areas with a high evaporation rate, translocation can become an effective mechanism leading to short-range contaminant transport even in a northern setting. Translocation is a process by which continual upward transport of porewater from the water table to the unsaturated zone by capillary suction is effected by high evaporation at the surface. Dissolved constituents are carried upward at the same time, frequently leading to the formation of efflorescent salts on the surface. Kwong et al. (1997) documented the upward transport of Zn and Cd during the dry seasons in the tailings pond of United Keno Hill Mines at Elsa (Table 2). The net result is the formation of

efflorescence on the exposed tailings surface composed dominantly of gypsum and minor bianchite (a zinc-rich iron sulfate hydrate, $(\text{Zn,Fe})\text{SO}_4 \cdot 6\text{H}_2\text{O}$). Most efflorescent salts are highly soluble. They are susceptible to flushing during heavy fall rain or spring freshet, leading to the transport of contaminants (zinc and sulfate for the Elsa tailings) to the receiving environment. Depending on the contaminant load and the prevailing volume of water for dilution, water quality criteria may or may not be met in the receiving environment.

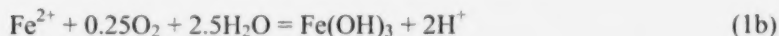
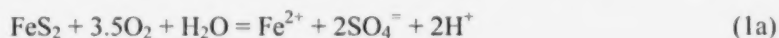
Table 2. Near-surface concentration of Zn and Cd in exposed tailings at Elsa suggestive of remobilization by translocation

Depth (cm)	Zn (%)	Cd (ppm)
0 - 25	1.33	180
25 - 36	1.17	180
36 - 55	0.83	120
55 - 70	0.83	73

In cold regions, another common process leading to the formation of efflorescence and enhanced probability of contaminant transport is incomplete sulfide oxidation. For example, complete oxidation of pyrite under warmer climatic conditions leads to the release of acidity and precipitation of iron oxyhydroxide (Equation 1):



The overall reaction can be broken down into two steps:



In northern regions, due to the low ambient temperature and high evaporation rate, the reaction given by Equation 1b may not occur or may only be partially completed. The increasing concentration of dissolved iron and sulfate in solution eventually leads to the formation of efflorescent iron sulfates like melanterite ($\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$), rozenite ($\text{FeSO}_4 \cdot 4\text{H}_2\text{O}$), copiapite ($\text{Fe}_5(\text{SO}_4)_6(\text{OH})_2 \cdot 20\text{H}_2\text{O}$) and others, depending on the extent of hydration and conversion of Fe(II) to Fe(III). These efflorescent salts represent temporary storage of acidity, leading to the possibility of acid generation and metal leaching in the downstream environment when dissolved and flushed. Moreover, during the formation of these secondary efflorescent salts, it is not uncommon for other potentially deleterious metals like Cu and Zn to be incorporated in their crystal lattice by coprecipitation (Alpers et al., 1994). Thus their dissolution may also lead to the direct release of deleterious metals *in situ*.

Finally, a contaminant remobilization process more unique to the northern settings is the potential release of adsorbed metals on oxyhydroxides under an ice cover. This process

commonly occurs in smaller streams. Under oxygenated conditions during the warm seasons, iron and/or manganese oxides/oxyhydroxides may form along the stream banks and streambeds, providing abundant sorption sites for dissolved metals in the drainage. As winter sets in with progressive formation of an ice cap, dissolved oxygen in the unfrozen stream flow can readily be consumed by metabolic activities of the resident organisms and/or decay of organic matter. This generates reducing conditions in the stream. Secondary oxides previously formed may become unstable and start to dissolve, releasing a concentration of adsorbed metals to the stream. It has been observed, for example, that the dissolved Mn concentration in Cristal Creek downstream of the Galkeno Mine in the Keno Hill mining district increases in the winter time under an ice cover (Environment Canada, unpublished data). Unfortunately, the correlation of manganese dissolution with other metal release has not been investigated in detail. MacGregor (this volume), however, has demonstrated the correlation of dissolved Mn with Zn in seepage originated from the Galkeno Mine.

In summary, as in southern climates, aqueous transport especially under acidic conditions dominates the dissipation of contaminants over a long distance in northern regions. Translocation processes may result in short-range contaminant transport towards the surface. Formation of efflorescent salts due to incomplete sulfide oxidation is more common in northern latitudes than in the temperate environments. Flushing of efflorescent salts is a major process of contaminant remobilization and transport to the receiving environment. Release of adsorbed metals accompanying dissolution of the secondary oxyhydroxide hosts in response to reducing conditions developed under an ice cover can also be common in northern streams.

Attenuation of Contaminant Transport in Cold Regions

Once contaminants are released into solution, their transport in the natural environment rarely remains unchanged. Under most situations, natural attenuation mechanisms soon become operative to restore chemical equilibrium and alleviate the potential for ecological disasters. Kwong and Whitley (1993) noted that contaminant attenuation mechanisms operative in northern drainage systems might include the following:

1. dilution and mixing;
2. precipitation and sorption; and,
3. particulate trapping by local flora.

The dominance of a particular mechanism or a combination thereof depends on the prevalent flow regime in a drainage system and can be indirectly affected by temperature. These attenuation mechanisms are briefly described below, culminated in a cursory examination of wetland processes, which may incorporate all of the above mechanisms.

Dilution and mixing: Inasmuch as contaminant toxicity often varies directly with concentration, dilution is an important contaminant attenuation mechanism that results in reduced environmental impacts. In addition to effecting reduction in contaminant concentration, the dilution process usually involves mixing of solutions of different composition. This in turn may lead to a variety of chemical reactions resulting in the

precipitation, coprecipitation or sorption of contaminants along the drainage flowpath. As an example, the effects of dilution and mixing on water chemistry and zinc distribution are well demonstrated by a series of streams located in the vicinity of Engineer Creek along the Dempster Highway. In this area, streams draining pyritic black shale rock units are usually acidic in character with elevated dissolved zinc and sulfate concentrations. Streams draining limestone-dominated rock units, however, have typically slightly basic pH and are devoid of significant dissolved loads of trace elements. When two streams of different composition meet to form a larger creek, dilution and mixing occur, resulting in an immediate neutralization of acidity. Moreover, both the dissolved sulfate and zinc concentrations in the neutral creek are reduced by as much as two orders of magnitude compared to the original acidic seep and the partitioning of zinc into the sediments is greatly enhanced (Table 3).

Table 3. Changes in water chemistry and zinc partitioning with dilution and mixing in a local drainage system near Engineer Creek, Dempster Highway

	pH	Sulfate (mg/L)	Dissolved Zn (mg/L)	Sediment Zn (ppm)
Acidic seep	3.0	21000	154	262
Acidic stream	3.4	3500	25	282
Neutral creek	6.8	736	0.54	5543

Precipitation and sorption: Mineral precipitation as a result of neutralization reactions and metal sorption with iron and manganese oxides/oxyhydroxides as well as clay minerals are well known contaminant attenuation mechanisms under all climatic conditions. They do not warrant further description. Of special interest in northern latitudes are cryogenic precipitation and the role microbes play in the precipitation and sorption processes. Cryogenic precipitation results from progressive freezing in a small body of water. When water starts to freeze, the remaining solution is increasingly enriched in dissolved constituents such that when the solubility product of a particular mineral is exceeded, that mineral precipitates out from solution. Vogt (1991) has described the precipitation of iron, silica and calcium carbonate by this process in detail. In all the study areas reviewed here, ferricrete formation is commonplace, resulting in permanent isolation of the adsorbed metals provided oxidizing conditions persist. In addition, in a small stream receiving discharge from the Onek adit in the Keno Hill mining district, Kwong et al. (1997) documented the cryogenic precipitation of hydrozincite ($\text{Zn}_5(\text{CO}_3)_2(\text{OH})_6$) along the streambed utilizing organic litter as nucleating sites. Sediment profiles in the vicinity suggests that rapid burial of the precipitate during flooding events has led to only minor re-dissolution. The aqueous transport of zinc is thus significantly attenuated by hydrozincite precipitation and the sorption of dissolved zinc onto iron oxyhydroxides along the stream banks and beds.

In spite of extreme climatic conditions in northern latitudes, microorganisms strive and play a significant role in attenuating contaminant transport. For example, Lawrence et al. (1998) examined the role of an algal mat in attenuating the contaminant load from a

groundwater discharge near a headwater stream in the Macmillan Pass area. Relevant data are extracted and shown in Table 4. The apparent ability of the algal mat to sequester various metals including Al, Co, Fe, Mn, Pb and Zn is impressive. The solution pH, however, has apparently not been affected by the algal mediation activities.

Table 4. Metal attenuation by a algal mat formation near the headwater of an acidic stream in the Macmillan Pass area

	Water above mat (mg/L)	Algal mat (ppm)	Water below mat (mg/L)
Al	156	3050	26.4
Co	0.25	700	0.04
Fe	298	290000	29.3
Mn	1.12	200	0.18
Pb	<0.02	5000	<0.02
Zn	5.0	150	0.88
pH	3.3	-	3.3

Particulate trapping by local flora: In all the areas examined, sphagnum moss is ubiquitous, especially lining acidic streams. The moss shows a great propensity to trap fine precipitates of iron oxyhydroxide, which is a renowned scavenger for dissolved metals and trace elements. Subsequent to a stream changing course, the sphagnum deposit eventually dries up and becomes partially lithified. An analysis of such lithified moss from an abandoned streambed in the Macmillan Pass area gave 68% Fe₂O₃, 4% P₂O₅, 2% SiO₂, 1% S, 26% LOI, 206 ppm As and 53 ppm Zn (Kwong and Whitley, 1993). Compared to the observed dissolved As concentration of 0.03 mg/L in the adjacent active stream, the attenuation of As transport by sphagnum moss with trapped iron oxyhydroxide is particularly noteworthy.

Wetland processes: In a natural wetland system, as well as most soil systems, all of the above-mentioned contaminant attenuation processes can occur. Largely due to mediation by sulfate reducing bacteria, however, sulfide precipitation often occurs in wetland systems to further limit the transport of most trace metals. In the Macmillan Pass area, Kwong and Whitley (1993) noted a significant reduction in dissolved zinc and other metal concentrations when acidic streams flowed through wetland areas prior to entering the major channel of the South Macmillan River. The detailed metal attenuation mechanisms occurring in the wetland, however, were not investigated. In wetland areas downstream of Clear Lake adjacent to a subcrop of massive sulfide mineralization, Kwong and Lawrence (1998) documented the microbial population and furnished evidence of pyrite and sphalerite precipitation. Both studies, however, were conducted in summer months when microbial activity was enhanced by the relatively warm conditions. There are numerous examples in the literature suggesting that wetland processes may not be effective at low temperature even at lower latitudes. Kwong and Van Stempvoort (1994) provided overwhelming evidence for attenuation of acid mine drainage (including reduction in dissolved copper and sulfate concentrations) in a natural wetland at the

abandoned Mount Washington Mine on Vancouver Island during late spring through late fall. However, year-round monitoring suggested that the wetland system served as a source instead of a sink for copper during the winter months and spring freshet (British Columbia Ministry of Energy, Mines and Resources, unpublished data). On-going research under the MiMi (Mitigation of the Environmental Impact from Mining Waste) Program in Sweden also shows that attenuation in metal concentration in a natural wetland in northern Sweden is mainly due to dilution (MiMi, 2001). Thus the functionality of wetland processes under low temperature conditions is in doubt.

Discussion

From the brief review of case studies of contaminant transport and attenuation processes occurring at four selected areas with mineralization in the Yukon Territory, it is evident that chemical weathering and metal leaching do occur in cold climates, resulting in the release of contaminants to the receiving environment. While contaminant transport is most obvious and hardly arrested in acidic drainage, it also occurs perhaps with less intensity under neutral conditions. The exposure and accumulation of reactive geologic materials (i.e., rocks and tailings susceptible to acid generation and metal leaching) by mining activities is thus unavoidably associated with the risk of environmental impacts. The major challenge of mine reclamation and decommissioning is to develop strategies that assure as negligible environmental risks and impacts as possible. Although nature has demonstrated many ways of attenuating contaminant transport as described above, such processes have seldom been utilized in a reclamation/decommissioning scheme to enhance the long-term chemical stability of the disturbed geologic materials. Some opportunities for further research to take advantage of what nature has to offer in developing practical solutions for mine reclamation and decommissioning are identified below. These ideas are presented in the form of a series of questions to stimulate the interested minds. It should be noted that encapsulation of reactive mine waste in frozen ground does take advantage of the unique conditions prevalent in arctic regions for mine waste management. The topic, however, is out of scope for the current review. Interested readers may want to refer to MEND (1993) for further information.

1. In addition to the renowned capacity of iron oxyhydroxide to scavenge dissolved metals and potentially deleterious trace elements, frequent freezing and thawing events occurring in northern streams enhance the aggregation of the usually fine precipitates to form ferricrete. Largely due to its physical properties, ferricrete is resistant to further weathering and transport and readily serves as a permanent sink for most potentially deleterious metals and trace elements as long as oxidizing conditions persist. One wonders if ferricrete behaves and can be potentially utilized the same way as hardpan formation in southern climates?
2. Cryogenic precipitation of carbonate species including calcium carbonate and hydrozincite frequently observed in small northern drainage systems demonstrates the stability of carbonates over a wide range of physico-chemical conditions in high latitudes. Does this further infer that carbonate sludge is more stable than hydroxide sludge in the northern environment? The voluminous hydroxide sludges have a limited stability field and require a larger facility for long-term disposal. Can the

current neutralization process of liming be modified to produce a denser and more stable carbonate sludge?

3. Dictated by the local physical, chemical and biological settings, site-specific mine reclamation or decommissioning schemes have to be developed to address the prevalent issues at a particular mine site. The complications of northern settings frequently preclude a direct transfer of technology developed for use in southern climates to northern latitudes. Do northern conditions dictate a combination of schemes to be used instead of relying on a single technology for mine reclamation or decommissioning? For example, can water management schemes be coupled with wetland systems to assure effective contaminant attenuation year-round?
4. As observed in the vicinity of the Dempster Highway and in the Macmillan Pass area, sphagnum moss and peat moss deposits generally abound in permafrost-rich regions. The moss deposits generally have high insulation values as well as capacity for sorption of various metals and trace elements? Does such moss have a role to play in reclamation or decommissioning schemes?

In short, given the noted sensitive ecosystem and extreme conditions occurring in high latitudes, it is more effective to work with nature instead of against nature in devising mine reclamation and decommissioning schemes to assure minimal environmental risks and impacts. With a bit of hard work and ingenuity, practical strategies can be devised to lessen the current reliance on dilution, mixing and neutralization as major mechanisms for attenuating contaminant transport in the northern environment.

Summary and Conclusion

Similar to what is commonly observed in southern latitudes, exposure and accumulation of reactive geologic materials during and post mining operations in northern regions may lead to the release of contaminants to the receiving environment through acid generation and metal leaching. Contaminant transport is enhanced in acidic drainage but is not necessarily negligible in neutral drainage. Short-range transport of contaminants from the saturated to the unsaturated zone by translocation can occur in exposed soils, sediments or tailings deposits with a high evaporation rate in all latitudes. In contrast, metal remobilization due to dissolution of secondary oxides with adsorbed metals under an ice cover is more unique to northern streams. Once contaminants are released to the aqueous phase, many natural mechanisms may occur to attenuate their transport in the receiving environment. Dilution and mixing especially with associated neutralization reactions are effective in reducing contaminant concentrations and are thus important attenuation mechanisms occurring in larger drainage systems. Cryogenic precipitation and trapping of iron oxyhydroxide with subsequent lithification may provide temporary or permanent metal attenuation. Although there is ample evidence that microbial mediation processes such as those occurring in wetland systems and algal mat formations are efficient in attenuating contaminant transport during the warmer seasons, their functionality under winter conditions requires further investigation. The challenge of mine reclamation and decommissioning in high latitudes lies in integrating chemical stability data with

information on site-specific conditions to take advantage of what nature has to offer to devise practical schemes with as negligible environmental risks and impacts as possible.

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